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Longitudinal Patterns in Fish Assemblages after Long-Term Ecological Rehabilitation in the Taizi River, Northeastern China

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Abstract: Fish assemblages inhabiting the Taizi River basin have been severely degraded by anthropogenic disturbances, which weaken the basin's ecological function and limited revitalization of the northeast industrial base. Long-term ecological rehabilitation has been conducted to restore the fish fauna and improve habitat conditions. To explore fish distribution patterns and key factors after this ecological rehabilitation, a comprehensive and detailed survey of fish fauna was conducted twice in 2021 at 33 sampling sites in the Taizi River. A total of 50 fish species from 13 families were collected, and the dominant species were *P. lagowskii*, *Z. platypus*, *C. auratus* and *P. parva*. Compared to results reported over the last decade, the increasing trend in fish richness and the change in the longitudinal fish organization were detected. The abundance variation for *P. lagowskii*, *Z. platypus*, *C. auratus*, *P. parva*, *R. ocellatus* and *H. leucisculus* along the upstream to downstream axis contributed most to the fish distribution pattern. Species replacement and addition might have jointly caused the longitudinal changes in the fish fauna, but species replacement was the main underlying mechanism. The canonical correspondence analysis (CCA) results show that the fish structure pattern was mainly shaped by cultivated land coverage and urban land coverage. Our study provides reference sites for future fish-based bioassessment and implications for region-specific management in the Taizi River.

Keywords: fish assemblage; fish zonation; environmental factors; Taizi River; management implication

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1. Introduction

Freshwaters comprise only 0.01% of the water on Earth but represent substantial biodiversity. Nearly 18,000 freshwater fish species, accounting for a quarter of known vertebrates, have been reported [1–3]. They play important roles in maintaining ecosystem functions and structures by means of the production and cycling of materials, and the exchange of energy [4]. Freshwater fish can also satisfy human demand for animal protein and are an important aspect of freshwater recreational activities. Nevertheless, anthropogenic activities, such as water pollution, biological invasion, dam construction and overfishing, have caused a notable decline in freshwater fish biodiversity (e.g., 78.3% of the freshwater fish fauna experienced biodiversity changes) during the past few decades [1,2,5,6]. Furthermore, the degree of vulnerability is increased by the fact that freshwaters receive wastes, sediments and pollutants through run-off from the surrounding terrestrial landscape, and due to their limited volume, they lack the capacity to mitigate the corresponding impacts [7,8]. Understanding the organization of fish and their structuring factors, in addition to providing theoretical advances, is also fundamental requirement in order to facilitate immediate action for mitigating the freshwater fish biodiversity crisis.

To explain patterns in riverine fish assemblages, many general conceptual frameworks have been proposed since at least the middle of the 20th century [9–16]. For example, based on differences in environmental factors and dominant species, Huet (1959) [14] divided a river into different zones along the upstream to mouth axis. Subsequently, Vannote et al. (1980) [15] proposed the River Continuum Concept to explain fish community structure in a near-pristine river basin. However, few rivers remain undisturbed by human activities. Thus, Ward and Stanford (1995) [16] proposed the Serial Discontinuity Concept to elucidate how the fish assemblages were structured in anthropogenic water bodies. These frameworks focus on the extrinsic factors that determine fish organizations. Indeed, extrinsic descriptors can elucidate fish pattern changes by two different processes, i.e., natural fluctuations and human pressures [17]. Current work in this area is not as concerned with the factors acting on fish organizations, but with which factors are the key to fish organizations in river systems [18–23].

Longitudinal changes in fish assemblage structures can result from two different processes: biotic zonation or cumulative addition of species downstream [24]. Biotic zonation refers to longitudinal species replacement as a result of discontinuities in river conditions [14,25]. In contrast, a more complex community downstream is observed due to the cumulative addition of species downstream [26,27], where environmental gradients from upstream to downstream areas contain smoothing transitions of extrinsic factors [24,28]. Rather than the terms "replacement" and "addition", some of the fish ecology literature instead uses "turnover" and "nestedness", respectively, to describe the same processes [29–31].

Monitoring fish communities and understanding the key factors in structuring fish assemblages are critical for the establishment and evaluation of management strategies [32,33]. The Taizi River represents an excellent model for studying spatial distribution patterns along the longitudinal gradient, since the human pressure variation is detected along the longitudinal direction. Following industrial, agricultural and urban development, the health of the Taizi River has deteriorated severely since the 1980s, and biodiversity conservation is currently a major management concern in the basin. Effective rehabilitative measures (e.g., fishing ban and eco-regulation for reservoirs) need to be continuously adjusted according to current biodiversity situations assessed by conducting research. During the past two decades, huge investments have been made to improve the habitat conditions on which biodiversity depends, such as through water pollution control and treatment, and afforestation (Figure 1) [34,35]. Furthermore, the change in the land use was detected in the Taizi basin during the past two decades (Figure 1). For example, the cultivated land coverage rate declined from 38.84% to 33.82% during 2000 to 2020 while the vegetative and artificial land coverage rates increased from 52.69% to 55.36% and from 8.47% to 10.83%, respectively. In contrast, conclusions regarding fish biodiversity have been drawn based on investigations mainly conducted during the period 2008 to 2010 [34,36–40], which are limited to the timely evaluation and improvement of management strategies.

In this study, updated baseline information on the diversity and longitudinal distribution of fish fauna in the Taizi River was obtained using a survey conducted at 33 sites in 2021. The specific objectives were to (1) explore the fish species composition and longitudinal fish assemblage patterns, as well as associated key environmental factors, after the ecological rehabilitation, (2) preliminarily analyze potential drivers causing changes in the longitudinal fish assemblage pattern, (3) explain the mechanism behind the shifts in the fish assemblage structure along the longitudinal gradient, and (4) suggest management implications accordingly.

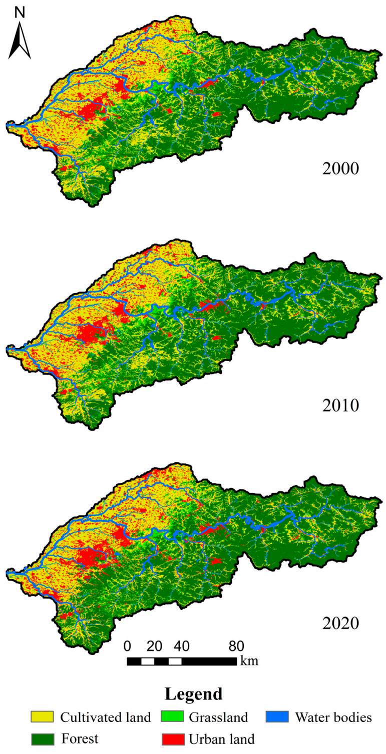

Figure 1. Land use changes during the period 2000 to 2020 in the Taizi River.

2. Materials and Methods

2.1. Study Area

The Taizi River (40°29′–41°39′ N, 122°25′–124°55′ E), one of the two largest tributaries of the Liaohe River, is located in Liaoning province of northeast China, with a drainage area of approximately 13,880 km^2 (Figure 2). The river originates in the Changbai Mountains and flows through important cities such as Benxi city, Liaoyang city, Anshan city and Haicheng city. The Taizi River is a typical temperate river with a length of 413 km. The annual average precipitation is 778.1 mm, and most of the precipitation occurred in the flood season from June to September. The average annual temperature ranges from 2.27 °C to 9.99 °C along the upstream to downstream axis, with a substantial temperature difference between winter (−9~−17 °C) and summer (22~24 °C). The Taizi River catchment has been spatially divided into three zones (upstream, midstream and downstream) along the longitudinal gradient based on biological and environmental data [41]. The obvious environmental interference gradient was observed in this basin. For example, three large reservoirs—Guanyinge (GYG) reservoir, Shenwo (SW) reservoir and Tanghe (TH) reservoir—were constructed in the last century (Figure 2). The geomorphological features of the basin include the upper–middle highland vegetation region and the lower-plain agricultural region. The highland region has a high percentage of natural vegetation cover with little human disturbance, whereas the plain region comprises mainly agricultural and urban land (Figure 1).

2.2. Field Sampling

A total of 33 sampling sites, consisting of 12 sites in the main stream and 21 sites in the tributaries, were surveyed seasonally in May and October 2021 (Figure 2). Sampling sites were selected in the field considering the representativeness and accessibility of the habitat.

Fish specimens were caught by electrofishing (Susan 1030S, China; 12 V import, 250 V export) and multi-mesh gill netting (30~50 m long, 1.5~2 m height, 1~4 cm mesh size from innermost nets to outermost nets) in different habitat units. The most suitable sampling method was employed in relation to the actual environment. Specifically, electrofishing along a stretch of 200~400 m stretch was carried out in narrow, lotic and shallow (depth less than 1.5 m) waters for about 40 min, and three gillnets were deployed in wide, sluggish and deep (depth more than 1.5 m) waters for about 2 h. Further, the length and height of multi-mesh gillnets, employed in the field work, needed to be adjusted according to the size and depth of micro-habitats at each sampling site. The impact of different sampling methods on survey results was minimized by controlling the range (e.g., sampling distance) and intensity (e.g., fishing time and frequency) to maintain similar fishing efforts. Individual specimens were identified to the species level, measured (standard length, mm), weighed (body weight, g) and released back into the river. Unidentified fishes were photographed, fixed in buffered formaldehyde (7%), and transported back to the laboratory for identification.

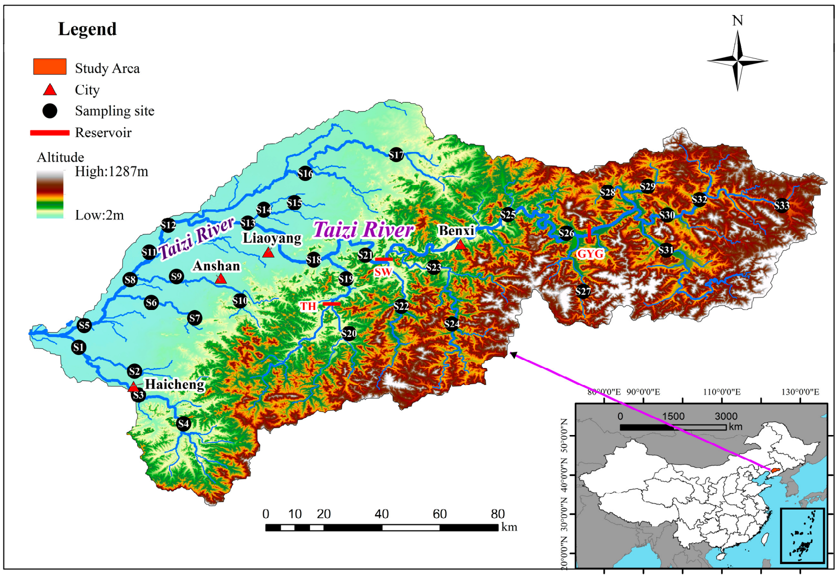

Figure 2. Sampling sites in the Taizi River.

Environmental factors were measured at the same time. Geographical coordinates and altitude (AL, m) were measured with the portable UniStrong G510. A YSI multi-parameter portable water quality analyzer was employed to detect water temperature (WT, °C), pH and dissolved oxygen (DO, mg/L) 3 times at each site. At least five measures were conducted in different transects for each site, and water depth (WD, m) and water width (WW, m) were estimated from the averages of these measures. Current velocity (CV, m/s) and water clarity (WC, cm) were measured using a Global Water FP211 current meter and a Sachs disk, respectively. In addition, water samples were collected, fixed with concentrated sulfuric acid (pH < 2) and immediately stored in a car freezer for laboratory determination of their chemical parameters. Hydro-chemical factors including chemical oxygen demand (COD_{Mn}, mg/L), total nitrogen (TN, mg/L), ammonium nitrogen (NH_4^+, mg/L), nitrite nitrogen (NO_2^-, mg/L), nitrate nitrogen (NO_3^-, mg/L), total phosphorus (TP, mg/L) and soluble reactive phosphorus (SRP, mg/L) were analyzed according to standard methods described in the Environmental Quality Standards for Surface Water (GB 3838-2002).

Since significant effects on riverine fish assemblages were reported as being a result of urban, grass, forest and cultivated land use [40,42,43], the GlobeLand30 map for 2020 was employed to extract these land use data for each site using ArcGIS 10.2 [44], and then analyzed the relationship between landscapes and fish assemblages.

2.3. Data Analysis

Frequency of occurrence (F_i%) and relative abundance (N_i%) were estimated for each fish species captured in this study. Fish species diversity was examined using the Margalef species richness index and the Shannon–Wiener diversity index [5]. These indices were calculated as follows:

$$F_i\% = L_i/L \times 100\%, \quad (1)$$

$$N_i\% = N_i/N \times 100\%, \quad (2)$$

$$D = (S - 1)/\ln N, \quad (3)$$

$$H' = -\Sigma P_i \ln P_i, \quad (4)$$

where $F_i\%$ is the frequency of occurrence for species i, L_i is the number of sampling sites where species i was collected, L is the total number of sampling sites, $N_i\%$ is the relative abundance for species i, N_i is the abundance of species i, N is the abundance of the total catch, H' is the Shannon–Wiener diversity index, D is the Margalef species richness index, S is the species number and P_i is the ratio between the number of species i and the total number of species.

To explore the longitudinal pattern in fish assemblages, the relative abundance data were adopted to establish a Bray–Curtis similarity matrix. Then, a cluster analysis was employed to clarify the degrees of similarity of fish communities among different sampling sites [45]. An analysis of similarity (ANOSIM) was used to test variations between different site-groups. The contribution of each species to differences between the assemblage groups was identified using similarity percentage analysis (SIMPER) [46]. All these analyses were carried out using the statistical program PRIMER V6.0 [47].

The variability in the corresponding fish abundance data in relation to potential environmental parameters was explored by canonical correspondence analysis (CCA), because the CANOCO Advisor suggested a unimodal model (gradient length = 4.1) would best fit our data. Before this analysis, differences in environmental factors between site-groups were tested using the Kruskal–Wallis nonparametric test. Furthermore, correlations among environmental variables were examined by Pearson correlation analysis. Environmental parameters that showed no significant spatial differences ($p < 0.05$) and had high correlation with other parameters (correlation coefficient > 0.7) were excluded from further analysis. Fish abundance data were transformed by square-root to meet the assumptions of multivariate normality and to moderate the influence of outliers. Forward selection was employed to further screen explanatory variables [48]. The statistical significance of the CCA gradients was assessed using the Monte Carlo permutation test ($p < 0.05$). Analysis of correlation and nonparametric testing were performed using OriginPro 2021, and the CCA was performed using the statistical program CANOCO 5.0.

3. Results

3.1. Fish Composition

A total of 9021 specimens belonging to 7 orders, 13 families and 50 species were captured during the study period (Table S1, Figure 3). The total species richness index and Shannon–Wiener diversity index were 5.29 and 2.59, respectively (Figure 4). The most diverse family was Cypriniformes with 34 species (66.67% of the total species), followed by Perciformes (9 species); Siluriformes (3 species); and Salmoniformes, Gasterosteiformes, Petromyzoniformes and Cyprinodontiformes (one species for each). The fish assemblage in the whole Taizi River basin was dominated by *Phoxinus lagowskii* ($N_i\%$ = 28.95%), *Zacco platypus* ($N_i\%$ = 13.74%), *Carassius auratus* ($N_i\%$ = 9.19%) and *Pseudorasbora parva* ($N_i\%$ = 7.85%), exhibiting high frequencies of occurrence (63.64%~96.97%). The common species were *Hemiculter leucisculus* ($N_i\%$ = 4.63%), *Rhodeus ocellatus* ($N_i\%$ = 4.58%), *Oryzias latipes* ($N_i\%$ = 3.70%), *Rhinogobius cliffordpopei* ($N_i\%$ = 3.29%), *Huigobio chinssuensis* ($N_i\%$ = 3.01%), *Pungitius sinensis* ($N_i\%$ = 2.45%), *Acheilognathus macropterus* ($N_i\%$ = 2.31%), *Cobitis sibirica* ($N_i\%$ = 2.27%) and *Rhinogobius giurinus* ($N_i\%$ = 2.11%), exhibiting moderate frequencies of occurrence (27.27%~54.55%). The remaining specimens (11.97% relative abundance) were classified into the rare species involving 37 species, and these species showed low relative abundance (less than 2.00%). Moreover, according to the Chinese Red

List [49], Least Concern and Data Deficient fish species were the most common in abundance, accounting for 98.0% of the total. Only one vulnerable species, *Lampetra reissneri*, was collected in this study.

Figure 3. Fish composition of the Taizi River.

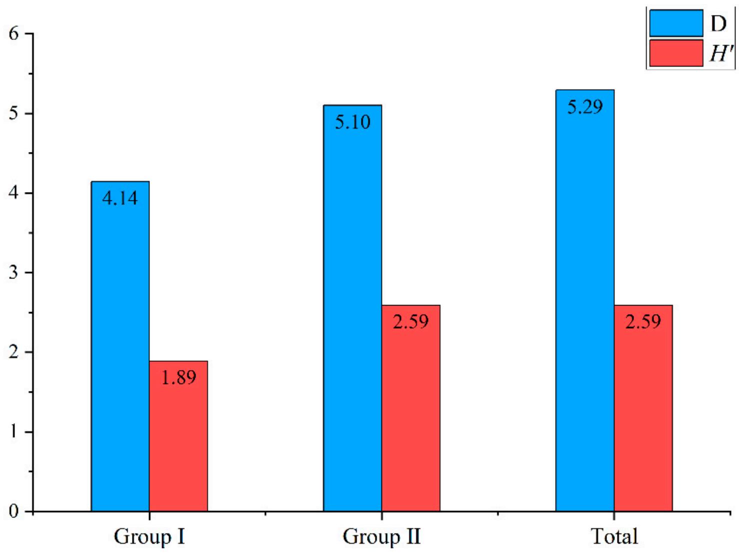

Figure 4. Spatial variances of species diversity for different groups. *H′* and *D* represent the Shannon–Wiener diversity index and the Margalef species richness index, respectively.

3.2. Spatial Distribution Pattern of Fish Communities

The cluster analysis with the relative abundance of fish data showed that all sampling sites could be divided into two site-groups (Figure 5). An analysis of similarity (ANOSIM) further confirmed that there were significant differences between the two groups (R = 0.832, $p < 0.01$). Group I consisted of 14 sampling sites in the middle–upper reach belonging to the highland zone with high vegetation coverage and weak human disturbances, while Group II consisted of 19 sampling sites in the lower reach belonging to the plain zone with serious human disturbances (Figure 2). The boundary between the highland zone and the plain zone was at or near that between midstream and downstream. The average altitudes were 231.79 ± 111.20 m for the highland zone and 26.11 ± 12.93 m for the plain zone, respectively. The estimated species richness index and Shannon–Wiener diversity index for Group II were higher than those for Group I (Figure 4). The three large reservoirs were located at or near the splitting boundary of fish assemblages (Figure 1).

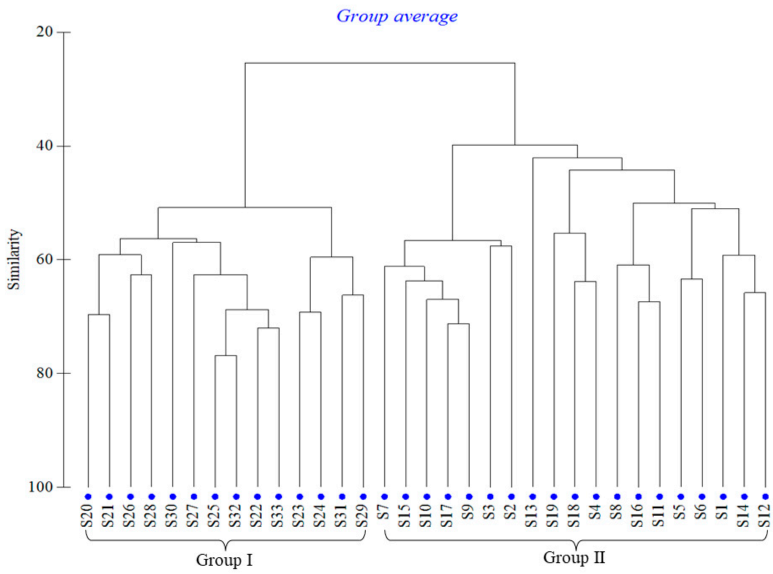

Figure 5. Classification of fish assemblages in the Taizi River based on the Bray–Curtis similarity.

SIMPER analysis showed that the between-group dissimilarity reached 87.45%. Fifteen species contributed more than 90% of the observed dissimilarity in the fish assemblages (Table 1). Group I was dominated by intolerant fish species. Indicative species for Group I contained *P. lagowskii*, *Z. plantypus*, *R. cliffordpopei*, *H. chinssuensis*, *P. sinensis*, *C. sibirica*, *O. obscurus* and *B. nuda*, with average abundances from 7.71 to 221.86, while Group II was characterized by tolerant fish species. Indicative species for this group included *C. auratus*, *P. parva*, *R. ocellatus*, *H. leucisculus*, *O. latipes* and *A. macropterus*, with average abundances from 10.11 to 40.74.

Table 1. The average abundances and percentage contributions of indicative species between site-groups.

Species	Average Abundance		Contribution%
	Group I	Group II	
P. lagowskii	221.86	1.89	35.59
Z. plantypus	57.07	35.84	10.96
C. auratus	9.57	40.74	6.56
P. parva	9.79	35.58	6.18
R. ocellatus	2.07	24.89	4.29
H. leucisculus	0.5	24.37	4.25

Table 1. *Cont.*

Species	Average Abundance		Contribution%
	Group I	Group II	
R. cliffordpopei	20.93	1.26	3.63
O. latipes	0.21	18.63	3.54
H. chinssuensis	18.71	3.53	3.08
P. sinensis	16.36	0.21	2.91
C. sibirica	18	0.47	2.84
A. macropterus	2.93	10.11	2.07
R. giurinus	7.86	7.21	1.77
O. obscurus	7.71	0.26	1.76
B. nuda	9.43	0.16	1.53

3.3. Correlation between Fish Assemblage Structure and Environmental Factors

Fourteen of the selected environmental parameters, comprising altitude, water depth, current velocity, water temperature, dissolved oxygen, chemical oxygen demand, soluble reactive phosphorus, total nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, forest land coverage, artificial land coverage and urban land coverage, showed significant differences between downstream and mid-upstream areas. Specifically, altitude, current velocity, dissolved oxygen and forest land coverage decreased downstream along the longitudinal gradient, while water depth, water temperature, chemical oxygen demand, soluble reactive phosphorus, total nitrogen, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, artificial land coverage and urban land coverage increased downstream. However, the remaining environmental parameters, including water clarity, water width, pH, total phosphorus and grass land coverage, did not vary significantly between downstream and mid-upstream areas (Table 2).

Table 2. Mean values and standard errors of different environmental variables for the 33 sites in the downstream and mid-upstream Taizi River.

Variables	Mid-Upstream	Downstream	*p*
AL (m)	231.79 ± 111.20	26.11 ± 12.93	0.000 **
WC (cm)	44.29 ± 24.56	42.47 ± 27.17	0.845
WD (m)	0.47 ± 0.28	0.89 ± 0.56	0.014 *
WW (m)	84.43 ± 65.78	94.53 ± 78.17	0.698
CV (m/s)	0.38 ± 0.18	0.21 ± 0.18	0.014 *
WT (°C)	15.59 ± 1.52	17.42 ± 2.01	0.008 **
DO (mg/L)	10.93 ± 0.7	9.89 ± 1.32	0.015 *
pH	8.39 ± 0.22	8.30 ± 0.22	0.286
COD_{Mn} (mg/L)	2.17 ± 0.36	4.88 ± 1.76	0.000 **
TP (mg/L)	0.17 ± 0.25	0.33 ± 0.20	0.053
SRP (mg/L)	0.03 ± 0.02	0.08 ± 0.09	0.031 *
TN (mg/L)	2.75 ± 0.43	5.46 ± 2.24	0.000 **
NO_3^--N (mg/L)	1.14 ± 0.31	1.91 ± 0.53	0.000 **
NH_4^+-N (mg/L)	0.20 ± 0.09	0.97 ± 1.056	0.011 *
NO_2^--N (mg/L)	0.004 ± 0.007	0.14 ± 0.11	0.000 **
CL (%)	0.22 ± 0.09	0.61 ± 0.23	0.000 **
For (%)	0.66 ± 0.17	0.10 ± 0.15	0.000 **
Gra (%)	0.07 ± 0.07	0.06 ± 0.07	0.509
UL (%)	0.05 ± 0.04	0.23 ± 0.13	0.000 **

* $p < 0.05$; ** $p < 0.01$.

The Pearson correlation analysis identified seven factors (altitude, chemical oxygen demand, forest land, nitrite nitrogen, nitrate nitrogen, soluble reactive phosphorus and total nitrogen) that were strongly related with at least one other factor (Figure 6). Based on the significance test and correlation analysis, the seven factors were retained and used in the initial CCA, and eventually two variables (cultivated land and urban land) were recommended as the key factors (Table 3). 38.5% of the variation in fish assemblages was explained by these two factors, with cultivated land and urban land accounting for 28.3% and 10.2%, respectively.

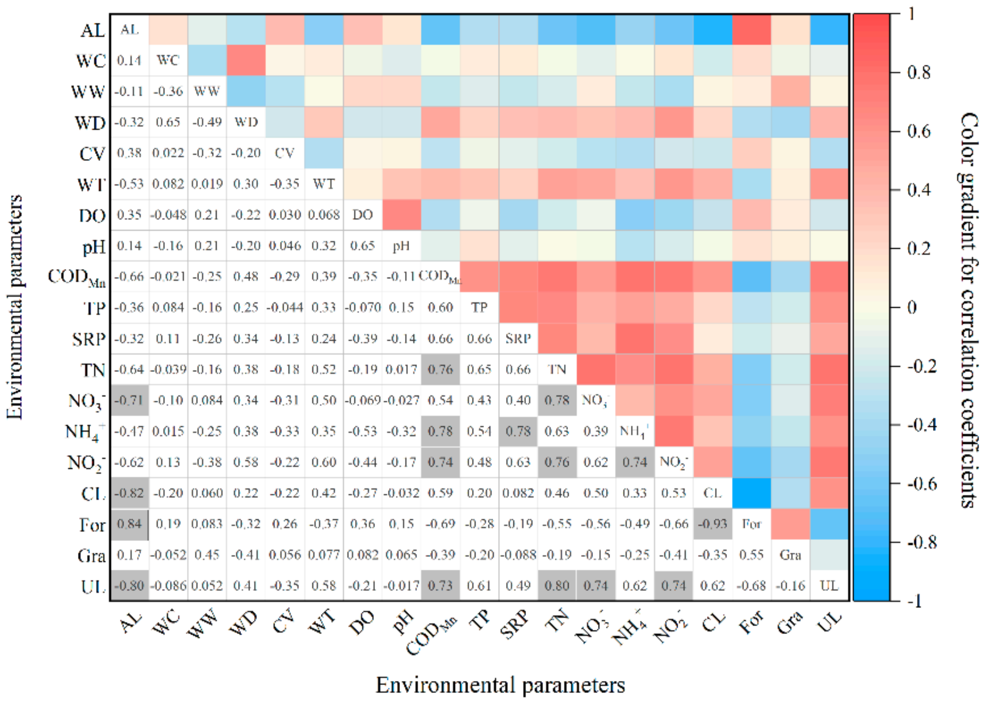

Figure 6. Correlation analysis among environmental factors. The boxes in different colors represent the color gradient for correlation coefficients, and the numbers in grey boxes represent the absolute values for the correlation coefficients are more than 0.7.

Table 3. Percentage of variance explained by the environmental variables used in the CCA.

Factors	Explained %	Contribution %	Pseudo-F	*p*
CL	28.3	56.7	12.2	0.002
UL	10.2	20.4	4.9	0.002
CV	3.0	6.1	1.5	0.120
WT	2.7	5.4	1.4	0.198
WD	2.5	5.0	1.3	0.228
NH_4^+-N	2.0	4.1	1.0	0.412
DO	1.1	2.2	0.5	0.876

The ordination plot indicates that the tolerant species (e.g., *C. auratus*, *P. parva*, *R. ocellatus*, *H. leucisculus*, *O. latipes* and *A. macropterus*), dominant in the downstream reaches, preferred habitats with high cultivated and urban land coverage. In contrast, the intolerant fish species (e.g., *P. lagowskii*, *Z. plantypus*, *H. chinssuensis*, *P. sinensis*, *C. sibirica*, *O. obscurus* and *B. nuda*), prevailing in the middle–upper reaches, preferred habitats with low cultivated and urban land coverage (Figures 7 and 8).

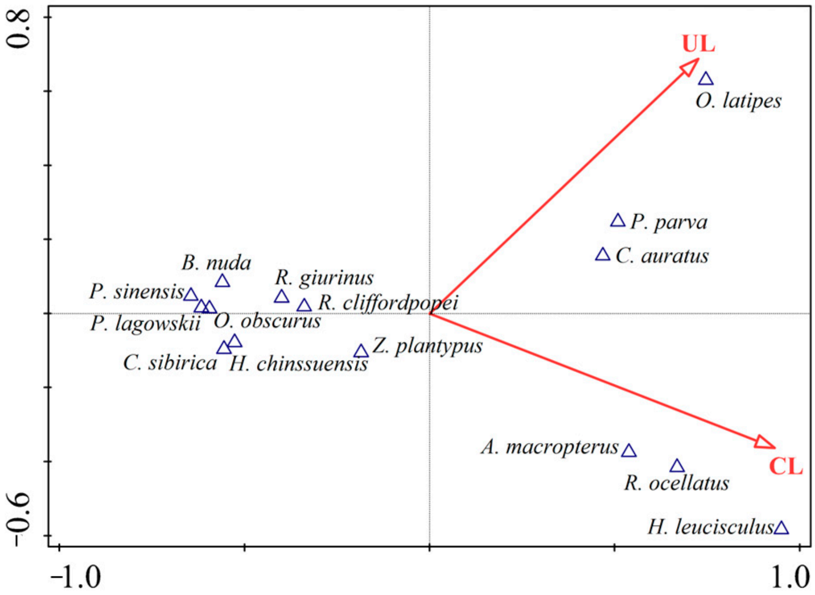

Figure 7. The relationships between fish assemblages and environmental parameters shown by CCA ordination plots.

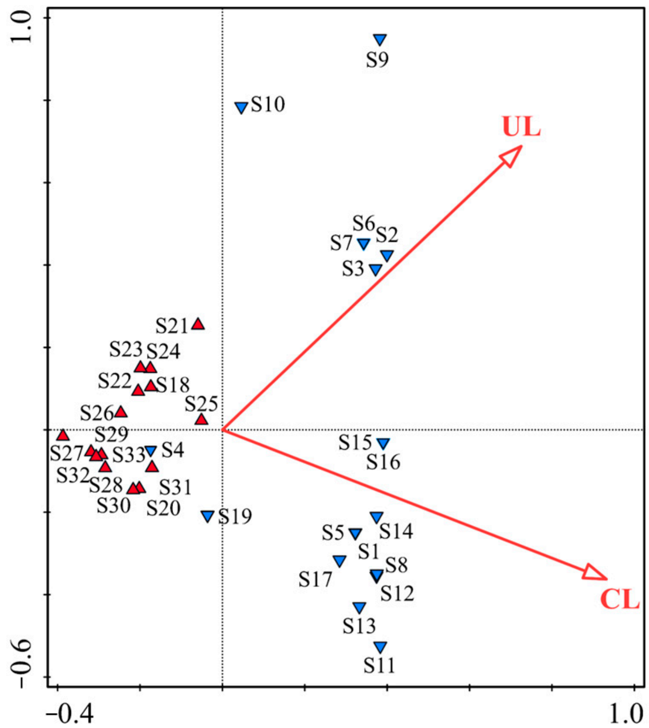

Figure 8. The relationships between sampling sites and environmental parameters shown by CCA ordination plots. The red triangles represent the sites located mid-upstream, while the blue triangles represent the sites located downstream.

4. Discussion

4.1. Species Composition

This study provides a comprehensive update in respect of the fish fauna in the Taizi River over a decade. A total of 50 fish species belonging to 7 orders and 13 families were collected, and the fish fauna, dominated by *P. lagowskii*, *Z. platypus*, *C. auratus* and *P. parva*, was characterized by small fish. Compared with fish species richness indices (3.50~4.83) estimated from investigations during the period 2008 to 2010 [36,38–40], the increasing rates ranging from 9.5% to 51.1% were observed. Nevertheless, when examining the dominant fish species composition data, reductions in relative abundance and species number were detected for intolerant fish species, while the inverse situation was observed for tolerant fish species. Since the early 21st century, state and local governments have taken action (e.g., water pollution control, water pollution treatment, afforestation and seasonal fishing bans) to improve habitat conditions and mitigate the freshwater fish biodiversity crisis to some extent [34,38,50]. Although these actions have partially restored fish assemblages and habitats, they cannot effectively prevent the fish fauna from degradation, indicating that the current ecological rehabilitation framework needs to be urgently evaluated and improved based on new research data.

4.2. Shifts in Longitudinal Fish Assemblage Patterns

According to distinct fish organizations, a river basin can be divided into different fish zones, and each fish zone is considered a homogeneous spatial unit [51,52]. Compared with the three fish zones reported by most research in the last decade [36,39,53], the two fish zones, only concordant with the result of Wang et al. [38], were proposed along the upstream to downstream axis in the Taizi Basin. The longitudinal pattern change might be resulted from (1) the anthropogenic habitat alteration gradient, (2) the cumulative impacts of dams, and (3) the environmental homogeneity between the upstream and the midstream areas.

Firstly, the environmental heterogeneity between downstream and mid-upstream areas, structuring the fish distribution pattern, was primarily induced by anthropogenic disturbances, which conclusion is supported by most of the environmental parameters with significant differences related to human interference (Table 2). For example, the CCA results show that cultivated land and urban land were the key factors shaping the spatial variations in fish communities in the Taizi River. Cultivated land coverage was higher in the downstream area, which indicates that intensive agricultural activities occurred there. Rivers in highly cultivated landscapes tend to have poor habitat quality due to higher inputs of sediments, nutrients and pesticides through surface run-off [42,54,55]. Furthermore, the lower basin is also an urban-, and industry-intensive area (Figures 1 and 2) [56]. Urbanization and industrialization generally lead to habitat degradation through ways involving hydrological instability induced by high impervious surface coverage and run-off conveyance, pollutant inputs, stream channelization, water temperature fluctuations induced by riparian vegetation degradation, and untreated sewage inputs [42,54,57]. Since ecological conditions were systematically degraded in the downstream catchment, sensitive species gradually disappeared from local communities, resulting in the reduction of local biotic heterogeneity [42,58,59]. Secondly, factors, involving zoogeography, physicochemical and biological conditions, and human-induced factors, have coupling effects on river fish assemblages [31,60]. The significant impact of dams cannot be ignored, even though their role is small relative to other factors. Our results show that three large reservoirs are located at or near the boundary of the two fish zones (Figure 2), highlighting that a small amount of variance in fish organization might be explained by the cumulative impacts of dams involving habitat alteration and artificial barriers [22,61–64]. Thirdly, a significant difference in only one of the environmental factors between the upstream and the midstream areas was detected (Table S2). Therefore, an increasing trend in the environmental homogeneity might lead to a decline in the dissimilarity of fish assemblages between these two regions.

4.3. Suggestions for Shortcomings in the Use of Zonation Concepts

When zonation concepts are employed to explain the fish organization, some drawbacks have been identified. For example, zonation concepts are used for description rather than explanation of longitudinal changes. Another shortcoming of zonation concepts is that fish zones may be defined according to the appearance of local indicator species, which limits their widespread application [65–67]. For the lacking explanation for the longitudinal fish composition change, two processes, involving species addition and species replacement have been proposed [23,29,31,66]. Our SIMPER analysis showed that changes in the average abundances of *P. lagowskii*, *C. auratus*, *P. parva*, *R. ocellatus*, *H. leucisculus*, *R. cliffordpopei*, *O. latipes*, *H. chinssuensis*, *P. sinensis*, *C. sibirica*, *A. macropterus*, *O. obscurus* and *B. nuda* explained most of the variance in the longitudinal fish organization pattern (Table 2 and Table S1). In addition, species richness and diversity tended to be higher in the downstream zone (Figure 4). Thus, such a longitudinal pattern was probably due to a combination of species replacement and addition, but species replacement was the main underlying mechanism.

To overcome the dependence on the occurrence of indicator species, zonation concepts can be refined by a new classification system (e.g., general biocoenotic terms and the intensity of human activities) [65–67]. In the Taizi basin, anthropogenic disturbances were the key drivers in shaping the longitudinal fish organization pattern. The downstream region was severely disturbed, which was characterized by tolerant fish species, while the mid-upstream region was slightly disturbed, which was characterized by intolerant fish species. Therefore, we suggest that the downstream and mid-upstream regions could be classified as the disturbed fish zone and undisturbed fish zone, respectively, according to the degree of human-induced influences.

4.4. Implications for Protection and Rehabilitation

Since few rivers currently remain undisturbed by human activities [2,6,68], bioassessment has been increasingly conducted to detect human alterations to river systems at regional, national and global scales using extensive fish datasets [18,67,69–71]. The selection of reference sites is an essential issue in fish-based bioassessment [66,72], and our results reveal that reference sites can be selected in the near-pristine mid-upstream region. Furthermore, the health of the river ecosystem is crucial for social and economic development around the basin due to its ecological service function (e.g., water supply, food supply, power supply, habitat supply, pollutant degradation, recreation). As important components of the health of rivers, fish assemblages and associated habitats in the Taizi River basin have been severely degraded by anthropogenic disturbances, which weakens the basin's ecological function and limits revitalization of the northeast industrial base. Consequently, the long-term ecological rehabilitation (e.g., water-quality improvement, fishing bans, afforestation and river management) has been conducted since the early 21st century. Nevertheless, relevant measures are not adjusted according to local conditions. In this study, distinct spatial structures in fish assemblages and environmental factors have been detected. The mid-upstream region is near-pristine, and the survival of sensitive fish species (e.g., vulnerable species) is heavily dependent on the habitat quality in this region. To protect this hotspot, we propose that the establishment of a conservation area, a long-term fishing ban, and comprehensive monitoring and assessment programs should be preferentially applied. In contrast, the human-induced impairment in the downstream region is severe, indicating that regional-scale ecological rehabilitation is urgently needed in this area. We suggest that priority should be given to measures including updating and improvement of fishery statutes, evaluation of coupling effects for multiple pressures, anthropogenic pressure regulation (e.g., water pollution control, eco-regulation for reservoirs, landscape regulation and river bed regulation), regional-scale habitat rehabilitation (e.g., riparian vegetation restoration, afforestation and water-quality improvement) and eco-compensation.

4.5. Limitations

Due to the previous data deficiency, our results were solely contrasted with the data estimated from the published literature to preliminarily analyze the impact of the restoration. However, owing to not exact replication in the methods (e.g., sampling season and specific sampling site), our conclusions drawn from the comparison could be slightly biased. Moreover, although two fishing gears were used to collected the samples in our study, and each gear has its own sampling bias, the impact was minimized by maintaining similar fishing efforts and using multi-mesh gill nets. Further, the species cumulative curve was better represented by an asymptotic curve than by a linear relation, highlighting that our survey results are considered sufficient to describe the fish fauna in the Taizi River (Figure 9). Thus, sampling bias with regard to the type of fishing gears did not appear to drastically impact the investigation results. Nonetheless, the sampling bias for each fishing technique was not quantitatively evaluated.

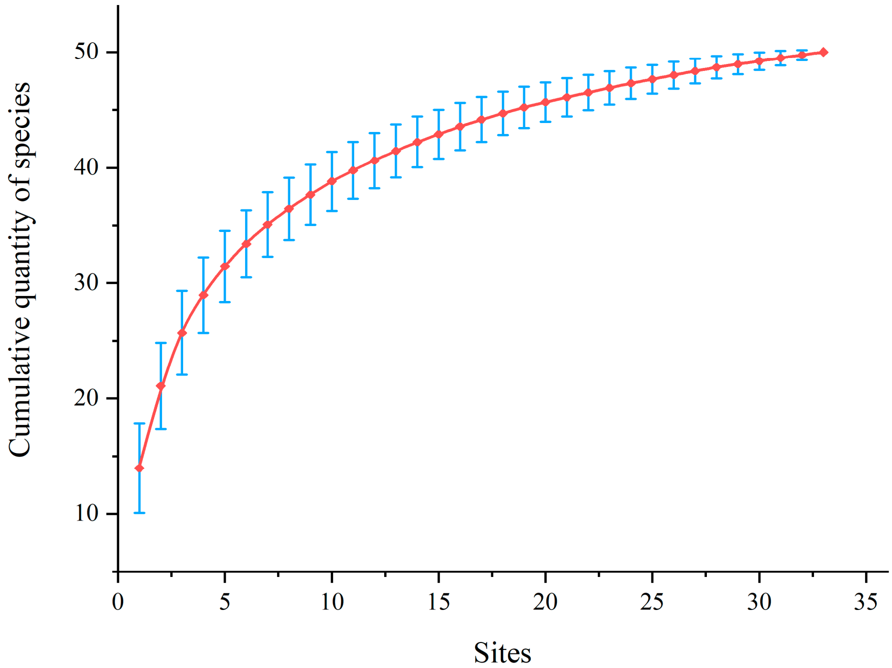

Figure 9. Fish species accumulative plot as an average of 999 curves based on different random orders of the sampling sites extracted (number of sites = 33). Vertical bars represent standard deviation.

5. Conclusions

The purpose of this study was to explore the changes in fish species composition and longitudinal fish assemblage patterns after long-term ecological rehabilitation in the Taizi River. A comprehensive survey of fish and environmental factors was conducted in 2021 and multivariate statistical analyses were performed on the relative abundances of fish and environmental parameters, to analyze the spatial organization of fish communities along the longitudinal gradient, determine key environmental drivers and provide implications for region-specific management accordingly. The main conclusions were as follows:

(1) A total of 50 fish species were collected and the dominant species were *P. lagowskii*, *Z. platypus*, *C. auratus* and *P. parva*. Although long-term ecological rehabilitation has restored the fish fauna to some extent, it cannot effectively prevent fish assemblages from degradation, indicating that the current ecological rehabilitation framework needs to be urgently evaluated and improved based on new research data.

(2) The fish assemblage could be divided into two fish zones along the longitudinal gradient. The spatial variance in fish assemblages was mainly determined by cultivated land coverage and urban land coverage. This fish organization pattern was probably due to a combination of species replacement and addition, but species replacement was the main underlying mechanism.

(3) The shift from three fish zones to two fish zones was detected for the longitudinal fish distribution pattern in the Taizi River. This change might be attributed to a combination of the increasing anthropogenic habitat alterations from the upstream toward

the downstream regions, the cumulative impacts of dams, and the environmental homogeneity between the upstream and the midstream regions.

(4) A disturbed fish zone and an undisturbed fish zone were proposed according the degree of human-induced influences. The management objectives should focus on natural habitat protection in the mid-upstream region, while ecological rehabilitation should be the main goal in the downstream region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142214973/s1, Table S1: Species composition in the Taizi River; Table S2: Mean values and standard errors of different environmental factors between the upstream, midstream and downstream regions.

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